Initiating a Benchmark for UML and OCL Analysis Tools

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Abstract. The Object Constraint Language (OCL) is becoming more and more popular for model-based engineering, in particular for the development of models and model transformations. OCL is supported by a variety of analysis tools having different scopes, aims and technological corner stones. The spectrum ranges from treating issues concerning formal proof techniques to testing approaches, from validation to verification, and from logic programming and rewriting to SAT-based technologies. This paper is a first step towards a well-founded benchmark for assessing validation and verification techniques on UML and OCL models. The paper puts forward a set of UML and OCL models together with particular questions for these models roughly characterized by the notions consistency, independence, consequences, and reachability. The paper sketches how these questions are handled by two OCL tools, USE and EMFtoCSP. The claim of the paper is not to present a complete benchmark right now. The paper is intended to initiate the development of further UML and OCL models and accompanying questions within the UML and OCL community. The OCL community is invited to check the presented UML and OCL models with their approaches and tools and to contribute further models and questions which emphasize the possibilities offered by their own tools.

1 Introduction

Model-driven engineering (MDE) as a paradigm for software development is gaining more and more importance. Models and model transformations are central notions in modeling languages like UML, SysML, or EMF and transformation languages like QVT or ATL. In these approaches, the Object Constraint Language (OCL) can be employed for expressing constraints and operations, thus OCL plays a central role in MDE. A variety of OCL tools is currently available, but it is an open issue how to compare these tools and how to support developers in choosing the OCL tool appropriate for their project. This paper puts forward a set of UML and OCL models together with particular questions for these models. This set of models is intended to be a first version of an OCL analysis tool benchmark to be developed within the OCL and UML community.

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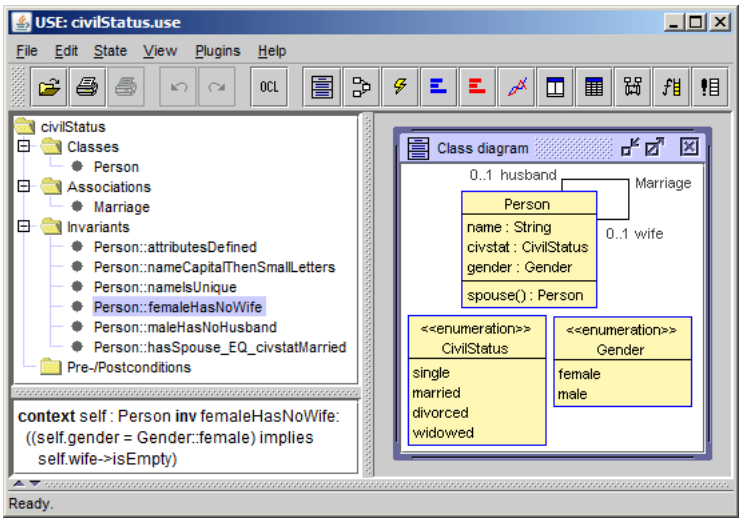
The current benchmark consists of four UML and OCL models: CivilStatus (CS), WritesReviews (WR), DisjointSubclasses (DS), and ObjectsAsIntegers (OAI). These models employ and emphasize different UML and OCL language features and pose different computational challenges for the analysis tools and their underlying technologies like provers, solvers, or finders: Plain invariants and enumerations in CS, association multiplicities in WR, classifier generalization in DS, and recursive operation definitions with inherited association ends and constraints in OAI. The accompanying questions can be roughly characterized by the partly overlapping notions consistency, independence, consequences, and reachability: under the label 'consistency' we discuss whether there exist object diagrams for the model at all, 'independence' concentrates on whether the invariants are non-redundant, 'consequences' studies how to formally deduce new properties from the explicitly stated ones, and 'reachability' focuses on how to characterize all object diagrams of a model and how to construct an object diagram with stated properties. The benchmark does not expect that all questions can be fully answered by a considered tool, but it expects that it is discussed to what extent and in which direction an approach or tool can help to answer the question.
The structure of the rest of this paper is as follows. Section 2 introduces the first version of our benchmark. Four example models with accompanying questions are introduced. As a proof of concept for the applicability of the models, Sect. 3 and Sect. 4 show how these models and questions are handled by two concrete tools and how the models must be fine-tuned to become processable by the respective tool. These two tools have been selected to illustrate how the models can be used to evaluate tools. Section 5 puts forward a list of topics that could be addressed in future work. Section 6 discusses related work and some (not all) approaches suitable to be subject to an OCL analysis tool benchmark. The paper is finished in Sect. 7 with concluding remarks. Furthermore, the paper is extended by an additional document [GBC13] in which all models are detailed in the formats `.use` and `.ecore` and all details of the benchmark examples for the tools USE and EMFtoCSP are made available.

2 Benchmark for UML and OCL Models (V-2013-02-01)

This section introduces the current benchmark models. We believe these four models offer a representative set of challenges and modeling language features.

2.1 CivilStatus (CS)

The simple class model in Fig. 1 with one class, one association, one operation defined with OCL, and two enumerations describes the civil status of persons. The six invariants require that (1) all attributes take defined values only, (2) the name attribute values follow a particular format, (3) the name attribute is unique among all persons, (4) a female person does not possess a wife, (5) a male person




```
context Person
  inv attributesDefined: name<>null and civstat<>null and
      gender<>null
  inv nameCapitalThenSmallLetters:
      let small:Set(String)=
        Set{'a','b','c','d','e','f','g','h','i','j','k','l','m',
            'n','o','p','q','r','s','t','u','v','w','x','y','z'} in
      let capital:Set(String)=
        Set{'A','B','C','D','E','F','G','H','I','J','K','L','M',
            'N','O','P','Q','R','S','T','U','V','W','X','Y','Z'} in
      capital->includes(name.substring(1,1)) and
      Set{2..name.size}->forAll(i |
        small->includes(name.substring(i,i)))
  inv nameIsUnique: Person.allInstances->forAll(self2|
      self<>self2 implies self.name<>self2.name)
  inv femaleHasNoWife: gender=#female implies wife->isEmpty
  inv maleHasNoHusband: gender=#male implies husband->isEmpty
  inv hasSpouse_EQ_civstatMarried: (spouse()<>null)=(civstat=#married)
```

Fig. 1. Class Diagram and Invariants for CS

does not possess a husband,[1] and (6) a person has a spouse, if and only if the civil status attribute holds the value married.

Questions: (Questions are given names in order to reference them)

ConsistentInvariants: Is the model consistent? Is there at least one object diagram satisfying the UML class model and the explicit OCL invariants?

Independence: Are the invariants independent? Is there an invariant which is a consequence of the conditions imposed by the UML class model and the other invariants?

Consequences: Is it possible to show that a stated new property is a consequence of the given model? As a concrete question in terms of the model, one may ask: Is the model bigamy-free? Is it possible to have a person possessing both a wife and a husband?

LargeState: Is it possible to automatically build valid object diagrams in a parameterized way with a medium-sized number of objects, e.g. 10 to 30 objects and appropriate links, where all attributes take meaningful values and all links are established in a meaningful way? For example, a female person named Ada could be married in role wife to a male person named Bob occupying the husband role. These larger object diagrams are intended to explain the used model elements (like classes, attributes and associations) and the constraints upon them by non-trivial, meaningful examples to domain experts not necessarily familiar with formal modeling techniques.

2.2 WritesReviews (WR)

The class model in Fig. 2 has the classes Paper and Researcher and two associations in between. The first two invariants (1) oneManuscript and (2) oneSubmission basically sharpen the 0..1 multiplicities to 1..1 multiplicities. The two invariants can be later be ignored for the construction of object diagrams. The next five invariants require that (3) a paper cannot be refereed by one of its authors, (4) the paper must obey a given length by restricting the attribute wordCount, (5) one of the authors of a studentPaper must be a student, (6) students are not allowed to review papers, and (7) there must be at least one student paper, but no more than 4 student papers are allowed (assumed that there are Paper objects at all).

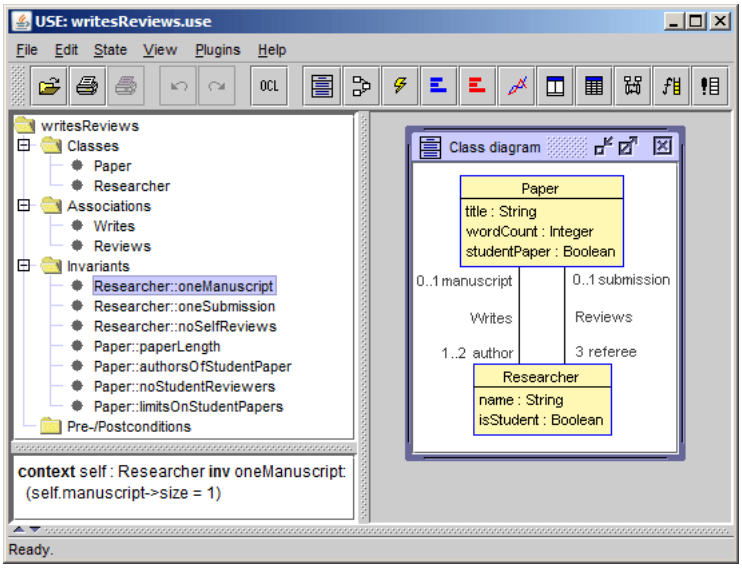
Questions:

InstantiateNonemptyClass: Can the model be instantiated with non-empty populations for all classes?

InstantiateNonemptyAssoc: Can the model be instantiated with non-empty populations for all classes and all associations?

InstantiateInvariantIgnore: Can the model be instantiated if the invariants oneManuscript and oneSubmission are ignored?

[1] We are aware of the fact that we are only dealing with 'traditional marriages' with traditional roles, and not with more modern concepts like 'common law marriages'.




```
context Researcher inv oneManuscript:
  self.manuscript->size=1
context Researcher inv oneSubmission:
  self.submission->size=1
context Researcher inv noSelfReviews:
  self.submission->excludes(self.manuscript)
context Paper inv paperLength:
  self.wordCount < 10000
context Paper inv authorsOfStudentPaper:
  self.studentPaper=self.author->exists(x | x.isStudent)
context Paper inv noStudentReviewers:
  self.referee->forAll(r | not r.isStudent)
context Paper inv limitsOnStudentPapers:
  Paper.allInstances->exists(p | p.studentPaper) and
  Paper.allInstances->select(p | p.studentPaper)->size < 5
```

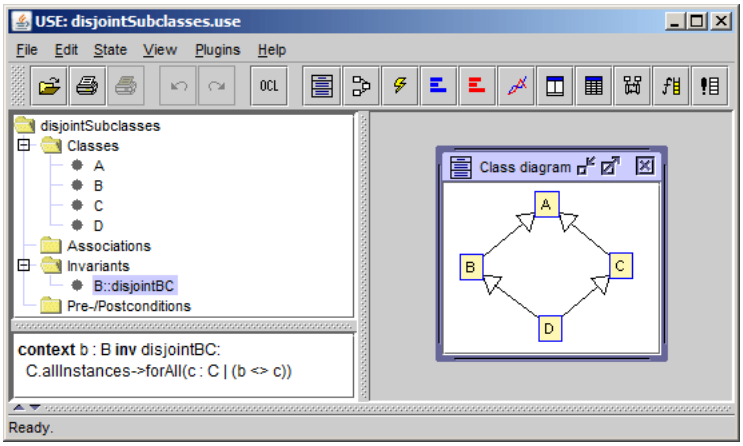
Fig. 2. Class Diagram and Invariants for WR

2.3 DisjointSubclasses (DS)

The class model in Fig. 3 shows an example for multiple inheritance. Class D inherits from class B and class C. Class B and class C are required to be disjoint by the stated invariant.

Questions:

InstantiateDisjointInheritance: Can all classes be populated? Is it possible to build objects for class D?




```
context b:B inv disjointBC: C.allInstances->forAll(c|b<>c)
```

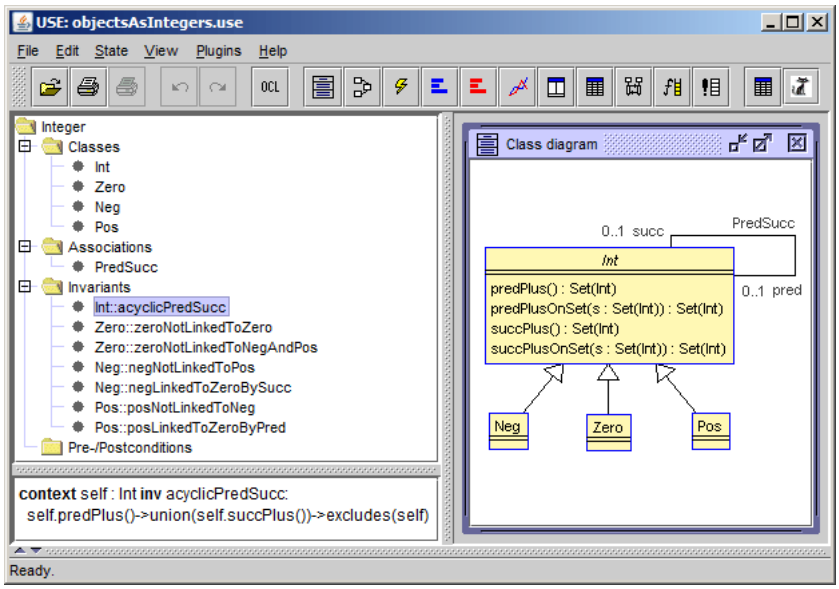
Fig. 3. Class Diagram and Invariants for WR

InstantiateMultipleInheritance: Can class D be populated if the constraint disjointBC is ignored?

A light extension of this benchmark model might add attributes a, b, c, and d to all classes having the type Integer. A hypothetical example constraint for class D might then require self.d=2*self.a. It would be interesting to see whether a tool syntactically allows to reference the attribute a from class D.

2.4 ObjectsAsIntegers (OAI)

The class model in Fig. 4 introduces one abstract superclass Int and three concrete subclasses Neg, Zero, and Pos. Objects of class Zero are intended to represent the integer 0, objects of class Neg are intended to represent a negative integer in the shape of a normal form (...((0-1)-1)...)-1, and objects of class Pos are intended to represent a positive integer in the shape of a normal form (...((0+1)+1)...)+1. The abstract class Int possesses one association which is inherited to the subclasses. The recursively defined operations predPlus() and succPlus() in class Int compute the (non-reflexive) transitive closure of the association ends pred and succ. The operations predPlusOnSet(...) and succPlusOnSet(...) are internal helper operations not intended to be called from outside the class. The invariants require that (1) the PredSucc links are acyclic, (2) a Zero object is not linked to another Zero object, (3) a Zero object is not linked to both a Neg and a Pos object, (4) a Neg object is not linked to a Pos object, and (5) a Neg object is linked to a Zero object by employing the succ association end. Pos objects are restricted analogously to Neg objects.




```
context Int
  inv acyclicPredSucc:
    predPlus()->union(succPlus())->excludes(self)
context Zero
  inv zeroNotLinkedToZero:
    not predPlus()->union(succPlus())->exists(i|
      i.oclIsTypeOf(Zero))
  inv zeroNotLinkedToNegAndPos:
    not predPlus()->union(succPlus())->exists(n,p|
      n.oclIsTypeOf(Neg) and p.oclIsTypeOf(Pos))
context Neg
  inv negNotLinkedToPos:
    not predPlus()->union(succPlus())->exists(p|
      p.oclIsTypeOf(Pos))
  inv negLinkedToZeroBySucc:
    succPlus()->exists(z|z.oclIsTypeOf(Zero))
context Pos
  inv posNotLinkedToNeg:
    not predPlus()->union(succPlus())->exists(n|
      n.oclIsTypeOf(Neg))
  inv posLinkedToZeroByPred:
    predPlus()->exists(z|z.oclIsTypeOf(Zero))
```

Fig. 4. Class Diagram and Invariants for WR

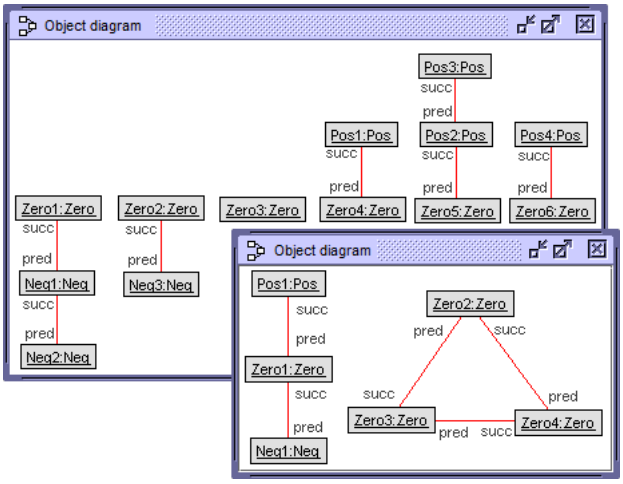


Fig. 5. Example Object Diagrams for OAI

The upper object diagram in Fig. 5 shows a valid system state for OAI, the lower one an invalid system state with some invariants violated. For example, invariant zeroNotLinkedToNegAndPos is violated in the left connected component of the lower object diagram. The upper object diagram displays the object representation of the integer sequence $-2, -1, 0, +1, +2, +1$. Every connected component of the object diagram corresponds to an integer. The lower object diagram has two connected components, where both components taken in isolation already violate the model invariants, but obey the class diagram multiplicities.

Questions:

ObjectRepresentsInteger: Is it true that any connected component of a valid object diagram for the model either corresponds to the term *zero* or to a term of the form $succ^n(zero)$ with $n > 0$ or to a term of the form $pred^n(zero)$?

IntegerRepresentsObject: Is it true that any term of the form *zero* or of the form $succ^n(zero)$ or of the form $pred^n(zero)$ corresponds to a valid object diagram for the model?

A slight extension of the current benchmark might ask a tool to find a minimal constraint subset (or all constraint subsets) such that the same invariants are implied as above.

3 Handling the Benchmark in USE

USE is a tool that allows modelers to check and test UML and OCL models. It allows model validation and verification based of enumeration and SAT-based techniques. USE allows the developer to construct object diagrams with a specialized language called ASSL (A Snapshot Sequence Language). All details can be traced from the provided additional material [GBC13].

3.1 CivilStatus (CS)

For the CS example, there are three procedures which aim to construct object diagrams: (1) generateWorld(numFemale:Integer, numMale:Integer, numMarriage:Integer) can build object diagrams satisfying all constraints and object diagrams violating particular constraints, (2) largerWorld(numFemale:Integer, numMale:Integer, numMarriage:Integer) can build larger object diagrams (up to 26 female persons and 26 male persons with at most 26 marriages) satisfying all constraints, and (3) attemptBigamy() tries to construct an object diagram including bigamy.

ConsistentInvariants: The consistency of the invariants in combination with the class diagram model inherent constraints is shown by a calling generateWorld(1,1,1) with all invariants activated.

Independence: The independence of the six invariants is shown by six calls to generateWorld(1,1,1) where before each single call exactly one invariant is negated and the other invariants are activated.

Consequences: The fact that the model is bigamy-free is demonstrated by a call to attemptBigamy(). In that procedure a large number of possible object diagrams with three persons and all possible assignments of roles and attribute values is considered and checked. No object diagram showing bigamy is found.

LargeState: A larger object diagram is constructed by the call largerWorld(5,7,4) which constructs a system state with five female persons, seven male persons, and four marriages.

3.2 WritesReviews (WR)

For the WR example, one ASSL procedure is provided: generateWorld(numPap:Integer, numRes:Integer, fillAttr:Boolean). The parameters determine the number of papers, the number of researchers, and whether the object attributes should be filled with actual values.

InstantiateNonemptyClass,InstantiateNonemptyAssoc: A call to generateWorld(4,4,false) yields the answer that no valid object diagram can be constructed. The attribute values are not taken into account. This shows that the multiplicities cannot be satisfied in the considered search space.

InstantiateInvariantIgnore: If the two invariants oneManuscript and oneSubmission are deactivated, a valid object diagram can be constructed by calling generateWorld(1,4,true). The attributes take meaningful values in the constructed object diagram.

3.3 DisjointSubclasses (DS)

For the model DS the ASSL procedure generateWorld(noA:Integer, noB:Integer, noC:Integer, noD:Integer) is employed.

InstantiateDisjointInheritance: A call to generateWorld(1,1,1,1) with invariant disjointBC activated does not yield a valid object diagram.

InstantiateMultipleInheritance: Calling generateWorld(1,1,1,1) with invariant disjointBC deactivated does return a valid object diagram, naturally with all objects of class D being also objects in class B and class C.

3.4 ObjectsAsIntegers (OAI)

For the model OAI, the ASSL procedure generateWorld(intNum:Integer, predSuccNum:Integer) constructs an object diagram with intNum objects for class Int and predSuccNum links between these Int objects. The constructed object diagram does not necessarily obey the invariants, but the results can be looked at being test cases for human inspection.

ObjectRepresentsInteger: We have generated various test cases with the above ASSL procedure and found no counter examples for the stated question resp. claim. However, we do not have solid formal arguments that the claim is valid.

IntegerRepresentsObject: One can formulate an ASSL procedure generateInt(i:Integer) that constructs the appropriate object diagram of class Int: Exactly one Zero object will be created; if $i < 0$, the respective number of Neg objects will be created and linked to the single Zero object in a correct way; if $i > 0$, the procedure will create Pos objects, analogously.

4 Handling the Benchmark in EMFtoCSP

Consistency checking and model instantiation are performed transparently in EMFtoCSP by internally creating a constraint satisfaction problem (CSP) that is satisfiable iff the model plus the OCL constraints satisfy the given correctness property. The user has to specify ranges for the class and association extents and for the attribute domains. All details are provided in the additional material [GBC13].

4.1 CivilStatus (CS)

For running the CivilStatus checks, the range 0..5 was used for the Person class and the range 0..25 for the Marriage association. The string length of the name attribute was set to 0..10 (EMFtoCSP supports the String datatype and its operations [BC12]). We omitted the invariants attributesDefined and nameCapitalThenSmallLetters. The first holds implicitly because of the search space configuration, the second currently cannot be parsed by the EMFtoCSP front-end.

ConsistentInvariants: The consistency of the invariants in combination with the class diagram inherent constraints is shown by running EMFtoCSP with the described search bounds, selecting 'weak satisfiability' as the verification property, yielding a valid object diagram as proof.

Independence: The independence of the four considered invariants is shown by verifying four modified versions of CivilStatus, where one of the invariants is negated in each run. Using the described search bounds, each run yields an instance that is valid w.r.t. the modified version.

Consequences: The fact that the model is bigamy-free is demonstrated by amending CivilStatus with a constraint notIsBigamyFree that requires an instance with bigamy and then showing the unsatisfiability of that model using the described search bounds.

LargeState: Adding an invariant niceInstance to CivilStatus restricts the names to a meaningful set and the gender to be consistent with the name (e.g., `name = 'Ada' implies gender = 1`). We set the search bounds to 7 persons and 3 marriages and EMFtoCSP yields a valid instance.

4.2 WritesReviews (WR)

For running the WritesReviews checks, 0..5 was used for both classes and 0..25 for both associations, the string lengths were set to 0..10 and the range of wordCount to 0..10000.

InstantiateNonemptyClass: Checking 'weak consistency' shows that the model and the constraints are unsatisfiability within the above search bounds.

InstantiateNonemptyAssoc: Checking 'strong consistency' shows that the model and the constraints are unsatisfiability within the above search bounds.

InstantiateInvariantIgnore: Checking 'weak consistency' on a modified version of WritesReviews, in which both oneManuscript and oneSubmission are commented out, yields a satisfying instance.

4.3 DisjointSubclasses (DS)

The front-end of EMFtoCSP does currently not support multiple inheritance, although the UML/OCL constraint library that is used in the background provides all necessary predicates.

4.4 ObjectsAsIntegers (OAI)

EMFtoCSP does currently not solve models with recursive operations.

5 Discussion

The benchmark as presented in this paper is a first step in the definition of a complete set of UML and OCL models that the modeling community could accept as valid. More importantly, the community could start to compare and to

improve current MDE approaches and tools, similar to what other communities in Software Engineering are already doing.

The models that we have discussed give a taste of the difficulties that anybody working on a new OCL analysis technique should consider. Nevertheless, our long term goal is the complete specification of a full benchmark model suite covering all known challenging verification and validation scenarios. The need for such a benchmark was one of the outcomes of the last OCL Workshop. However, the notion 'challenging scenario' is not universal and debatable, in the sense that depending on the formalism used by a given tool a scenario may be easy or extremely demanding. With proposing this benchmark and its hopefully coming evolution, we want developers to evaluate the existing approaches, realize which are the strengths and drawbacks of each one, and choose a tool or an approach according to their specific needs. Speaking generally, for an OCL analysis tool benchmark there are challenges in two dimensions: (a) challenges related to the complexity of OCL (i.e., the complete and accurate handling of OCL) and (b) challenges related to the computational complexity of the underlying problem. Both should be treated in the benchmark.

Based on our own experience we believe that at least the following scenarios should be covered by models in the benchmark:

1. Mostly local constraints: models with many constraints but where all constraints are local, i.e. they only involve a single class or a cluster of closely related classes.
2. Mostly global constraints: models with many constraints but where all constraints are global, i.e. they usually involve a large percentage of the classes in the model, e.g. a constraint forcing all classes in the model to have the same number of instances.
3. Models with tractable constraints, i.e., constraints that can be solved 'trivially' by simple propagation steps.
4. Models with hard, non-tractable constraints, e.g., representations of NP-hard problems.
5. Highly symmetric problems, i.e., that require symmetry breaking to efficiently detect unsatisfiability.
6. Intensive use of Integer arithmetic allowing large ranges for integer values and employing heavily arithmetic and operation like inequality.
7. Intensive use of Real arithmetic.
8. Intensive use of String values and operations on strings. So far, String attributes are mostly ignored [BC12] or simply regarded as integers which prohibits the verification of OCL expressions including String operations other than equality and inequality.
9. Many redundant constraints: is the approach able to detect the redundancies and benefit from them to speed up the evaluation?
10. Sparse models: instances with comparably few links offer optimization opportunities that could be exploited by tools.
11. Support for recursive operations, e.g. in form of fixpoint detection or static unfolding.

12. Intensive use of the 'full' semantic of OCL (like the undefined value or collection semantics); this poses a challenge for the lifting to two-valued logics.
13. Problems that have large instances (with many objects).

Alternative models for each of these scenarios should be part of the benchmark to cover different goals in the evaluation. For instance, when evaluating the correctness of the results provided by a given tool we should execute satisfiable and unsatisfiable versions of each model and when evaluating its performance and scalability we should feed the tool increasingly larger versions of the same model.
We hope that as soon as these benchmarks become available the interested community (from developers of tools to tool users) will start applying them on a variety of tools and approaches, which will allow us to clarify and better understand the differences among the plethora of approaches and tools for OCL solving that are now available. However, we have to keep in mind that as discussed in the previous section, the results of the benchmark have to be interpreted with care. A bad score of a tool for a given model can be attributed to different reasons, from a simple syntax problem (maybe the tool does not support one of the OCL operations used in an expression even if this operation is not a key part of the benchmark) to a limitation of the tool or a limitation of the underlying tool formalism. This difference is important too. In a further step, we want to able not only to compare the tools themselves but to use the benchmark to study the limits of frequently used provers, solvers or finders when applied to the OCL realm.

6 Potential Tools to be Considered and Related Work

We have conducted the benchmark with the tools USE [GBR07] and UMLtoCSP resp. EMFtoCSP [CCR07,GBCC12]. Other validation and verification tools for OCL which are possible candidates to be examined under the benchmark are UML2Alloy [ABGR10], the planned USE extension arising from [MB07], the ITP/OCL tool [CE06] and mOdCL [RD11]. Furthermore, the OCL tools OCLE, ROCLET, and OCTOPUS would be benchmark candidates, but the projects seem to be inactive since years (http://lci.cs.ubbcluj.ro/ocle/, http://www.roclet.org [dead link], http://octopus.sourceforge.net/).
There is variety of other validation approaches for OCL based on SMT [CEdD09,YA12] or SAT [WSD12]. Description logics has been used as a basis for OCL expressions and constraints [QACT12,CCGM07] and for querying UML class diagram models [CGOP12].
On the prover side HOL-OCL combines Isabelle with UML and OCL [BW08], the Key project attempted theorem proving in connection with the commercial UML tool Together [BGH+07], and encoding of OCL into PVS was studied in [KFdB+05]. We would expect that completeness problems as appearing in OAI ('Does the set of all object diagrams of the model correspond to the integers?') could be handled more adequately in proof-oriented approaches. An

application of a combination of proof and test techniques in connection with OCL was described in a case study [Sch10]. Elements from that work might be considered for future versions of the benchmark.

Testing approaches aiming at tool support were put forward in [CDJT11,AS05]. The benchmark might also be applicable for code generation as in Dresden OCL [HDF02] or MDT/OCL [Wil10]. Last, the feature model for model development environments [COD10] could be connected to the benchmark.

7 Conclusion

The approach proposed here is only first step towards a more complete benchmark. We concentrated on four models with eleven questions and claims. We already have a sufficient coverage of OCL and questions, but more models and items are needed. We would be happy if other groups would contribute. We think more elaboration on complexity questions should be done in order to answer, for example, questions attacking the extent to which a tool can produce and deal with larger states or assert properties in larger states. A classification of questions and items suitable for proof techniques or for test techniques seems to be needed as well.

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